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A MILLIMETER WAVE QUASI-OPTICAL MIXER AND MULTIPLIER

Report No. TR078
Final Report
JPL Contract No. 954492

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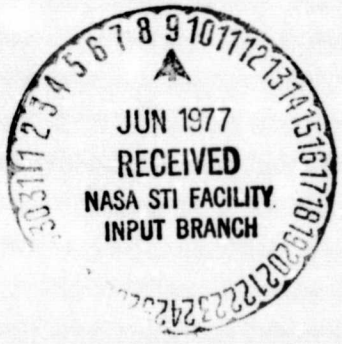
Prepared for:

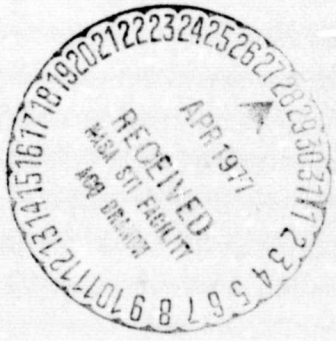
JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91003

Prepared by:

J.J. Gustincic
Consulting Engineer
13121 Mindanao Way
Marina Del Rey, California 90291

1 March 1977





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ABSTRACT

This report describes the results of an experimental study of a biconical quasi-optical Schottky barrier diode mount design which could be used for mixing and multiplying in the frequency range 200-1000 Ghz. The biconical mount is described and characteristics measured at 185 Ghz are presented. The use of the mount for quasi-optical frequency doubling from 56 to 112 Ghz is described and efficiency estimates given.

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1.0 INTRODUCTION AND SUMMARY OF RESULTS

This report describes the results of a six-man month experimental study undertaken to develop a non-waveguide quasi-optical Schottky barrier diode mount for use in single ended mixers and frequency multipliers. The objective of the study was to evolve a structure which could easily be scaled in frequency for use in the frequency range 200 to 1000 Ghz. Low frequency measurements indicate that Schottky diodes exist today with useful performance characteristics at these high frequencies, but little work has been done in providing structures to couple into the diodes at these short wavelengths.

The work described in this report centers around the use of a biconical antenna radiating structure for the diode mount. This mount can be constructed on a lathe and due to its simplicity, it lends itself well to the close tolerance requirements of the higher frequencies. The results of preliminary measurements on a mixer mount constructed for 1.5mm wavelengths are presents in Section 2. The radiation characteristics and I.F. impedance properties of the mount at 185 Ghz are given in Section 3. Measured mixer performance in a quasi-optical radiometer system at 185 Ghz is described in Section 3.3. First trial measurements yielded single sideband conversion losses of -13 db indicating some promise for this type of mount.

To demonstrate the feasibility of frequency multiplication with the diode mount, a completely quasi-optical frequency doubler working from 56 to 112 Ghz was constructed and is

described in Section 4. The experimental doubler was successfully used as a local oscillator source for an existing quasi-optical radiometer. Approximately 5mw of output was obtained with an input power of 70mw yielding an estimated efficiency of 7%.

2.0 THE BICONICAL QUASI-OPTICAL MOUNT

The general configuration of the quasi-optical mount is shown in Fig. 1. The Schottky Barrier chip and whisker are mounted at the apex of a length of biconical transmission line. The transmission line has a full flare angle of 46^{o} yielding a characteristic impedance of about 50Ω. The top and bottom sections of the biconical line are formed by two bullet shaped pieces as can be seen in the figure. The tips of the bullets have flats machined on them to provide mounting surfaces for the chip and whisker. The flats are 0.020 inches in diameter and are separated by 0.010 inches when the bullets are in place. The lower bullet mounts the whisker and is machined for a press fit into the base. This lower bullet is then analogous to the whisker post in a conventional waveguide mount. It is pushed forward through the base by a micrometer screw tool to make the whisker contact the chip. The chip is mounted to the upper bullet which in turn is insulated from the base and mount structure by means of a fiberglass bushing. The body of the bullet is threaded into the bushing which in turn is threaded into a hole in the mount structure. Electrical connection is made to the upper bullet by means of a center conductor rod extending down from a 50Ω OSM female bulkhead connector. The end of the rod is split with a saw cut and spread apart to make a positive friction contact in a hole drilled in the top of the upper bullet.

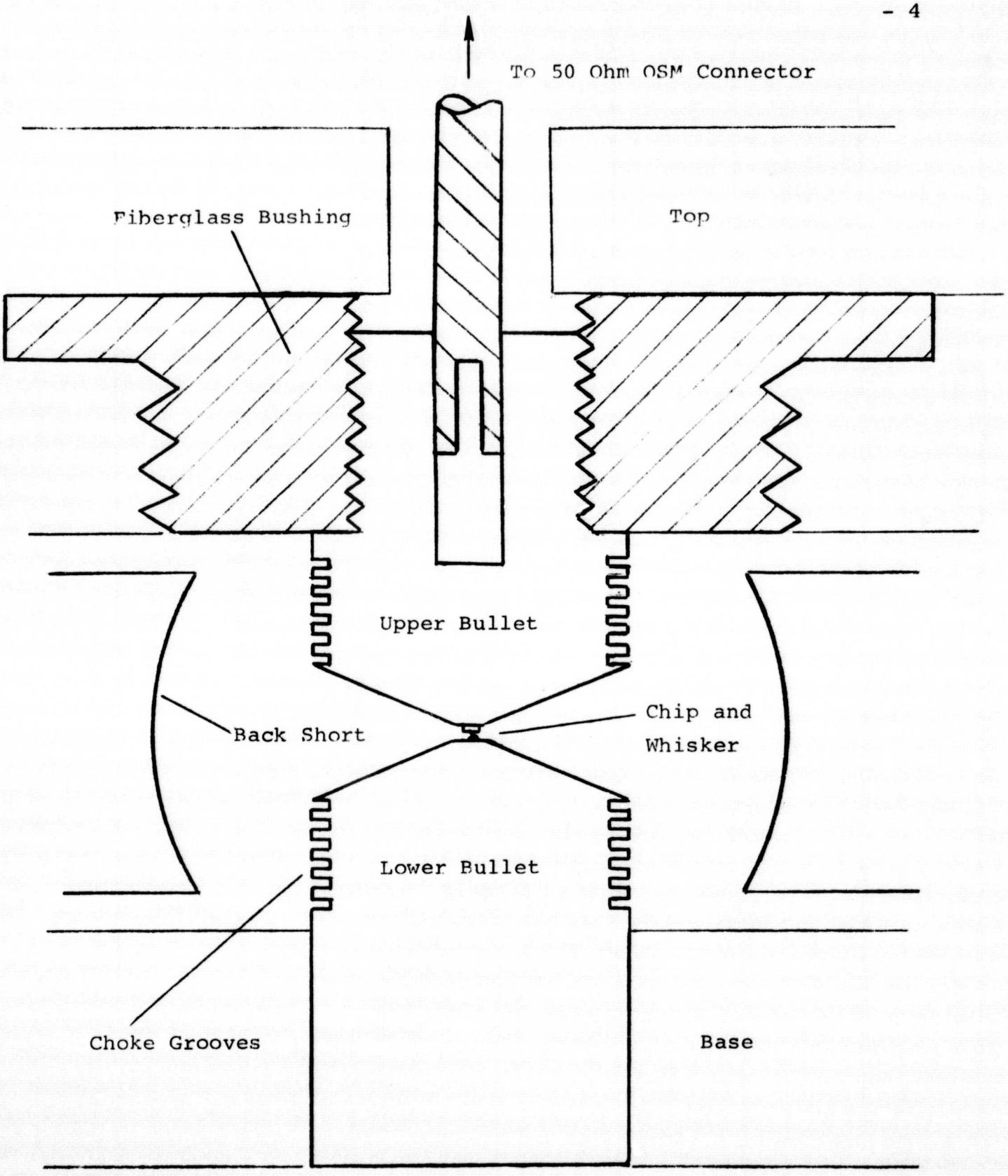

Figure 1. The General Configuration of the Biconical Mount.

A series of six equally spaced choke grooves are machined into the body of the bullets at the open end of the transmission line. The chokes are spaced one-half wavelength at the design frequency and are one-quarter wave deep. The open end of the transmission line forms a radiating aperture approximately four wavelengths in height. The choke grooves prevent any R.F. Currents from flowing on the body of the bullets thereby isolating the biconical radiator from the mount structure and 50Ω output line.

The biconical radiating aperture has circular symmetry and therefore has a receiving pattern which is uniform around the bullets. A more directive pattern is necessary to make the device compatible with existing quasi-optical circuitry. This directivity is achieved by means of a curved back-short which extends around the radiating aperture reflecting energy back to the whisker and chip. The curved back-short has a small directive receiving aperture located at the front of the mount and a moveable section located at the back of the mount which is used to resonate the geometry. The aperture in the back-short is a circular hole about 3.5 wavelengths in diameter. The moveable tuning section of the back-short is a rod four wavelengths in diameter which has a concave end and is threaded into a hole in the back of the back-short. The front of the back-short is faced off leaving a 0.01 inch thickness in the back-short wall at the radiating aperture so that multi-moding

effects do not occur in the short section of circular waveguide formed by this circular mode.

2.1 The Chip and Whisker

The Schottky Barrier chip is a 0.05 x 0.01 x 0.01 inch chip with 2.5μ dots furnished by R.J. Mattauch of the University of Virginia. The chip has a series resistance of 10Ω and a capacitance of .007pF. The chip is soldered indirectly to the flat on the upper bullet. A 0.005 inch high whisker with a single bend formed from 0.0005 inch dimaeter phosphor bronze wire is soldered to the flat on the lower bullet. The tip of the whisker is etched to a fine point $< 1\mu$ in diameter by an A-C etch current of 2ma in an etching solution of 25% NaOH in deionized water. The chip is whiskered by observing the whisker tip approach, the surface of the chip as the lower bullet is pushed forward. The final contacting is done in a "blind" fashion with the outcome of the last 5μ of a whisker travel determined by the random probability of hitting a diode dot. Satisfactory whiskerings in the order of 30% of those attempted were achieved by this technique. An electron micrograph of a whiskered chip at the center of the bicone is shown in Fig. 2.

Figure 2. An Electron Micrograph of the Whiskered Chip.

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2.2 Ohmic Losses in the Bicone

An estimate of the ohmic losses which exist in the bicone structure will not be obtained. The basic biconical antenna geometry is shown in Fig. 3. Assuming an outward propagating spherical wave traveling from R_1 to R_2, the friction of input power dissipated in the cone will be determined for the case of small metallic losses.

The outward propagating spherical wave has a single azimuthal component of magnetic field proportional to

$$H_\phi = \frac{1}{R \sin\theta} e^{-jk_o R} \tag{1}$$

The time average power crossing the $R = R_1$ sphere is given by

$$P_{in} = \frac{1}{2} Z_o \int_{\theta_o}^{\pi-\theta_o} \int_0^{2\pi} H_\phi^2 R_\phi^2 \sin\theta \, d\phi \, d\theta$$

$$= 2\pi Z_o \ln \cot \frac{\theta_o}{2} \tag{2}$$

where $Z_o = 377\Omega$ and θ_o is the half angle of the metallic cone as shown in the figure. The power lost in the metallic walls is given by

$$P_L = \frac{1}{2} 2R_s \int_{R_1}^{R_2} \int_0^{2\pi} H_\phi^2 \Big|_{\theta = \theta_o} R \sin\theta \, d\phi \, dR$$

$$= 2\pi R_s \frac{1}{\sin \theta_o} \ln \frac{R_2}{R_1} \tag{3}$$

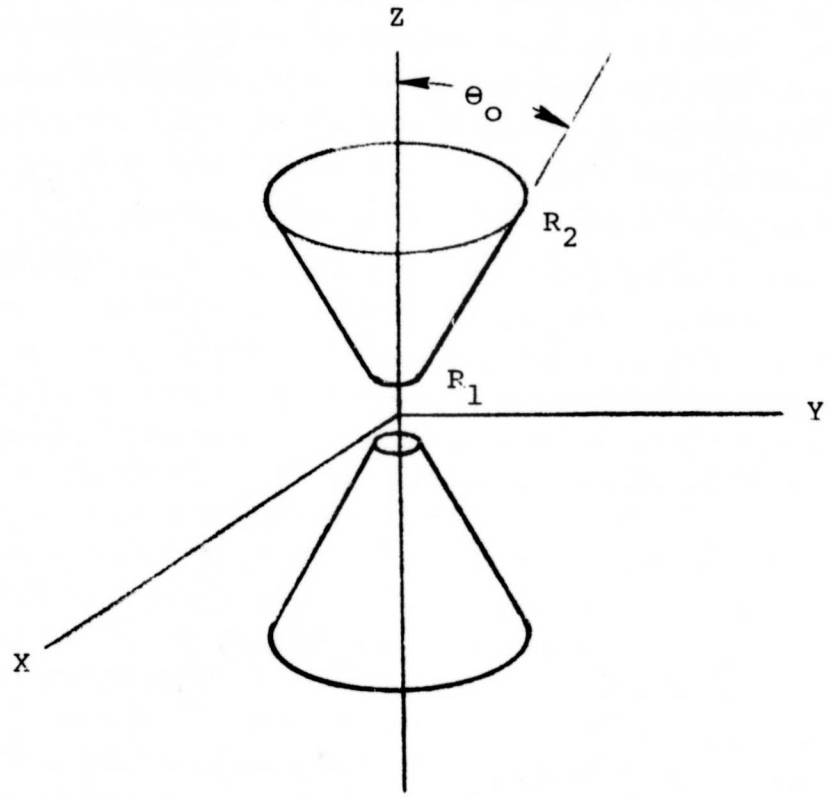

Figure 3. The Biconical Antenna Geometry.

where R_s is the skin resistance of the metal

$$R_s = \sqrt{\frac{k_o z_o}{2\sigma}} \tag{4}$$

and σ is the metal conductivity. The ratio between the power-lost and the power-input is obtained from Eqs. (2) and (3) as

$$\frac{P_L}{P_{in}} = \frac{R_s}{Z_o} \quad \frac{\ell n \frac{R_2}{R_1}}{\sin \theta_o \ \ell n \cot \frac{\theta_o}{2}} \tag{5}$$

where it has been assumed that all radii of curvature are large compared to the skin depth $\delta = 1/ R_s$.

TABLE I

		200 GhZ	600 Ghz	1000 GhZ
Silver:	$R_s(\Omega)$	.113	.196	.253
	δ (μ)	.142	.082	.064
Brass:	$R_s(\Omega)$	.225	.390	.503
	δ (μ)	.282	.163	.126

Table I gives values of skin depth and skin resistance for silver and brass at 200, 600 and 1000 GhZ. As can be seen the skin depths are typically a small fraction of a micron justifying the skin depth approximation for most practical geometries where the characteristic dimensions are no smaller than tens of microns.

Consider the practical case of a brass mount constructed for use at 200 Ghz. The pertinent design parameters would be

$$R_2 = .120 \text{ inch}$$
$$R_1 = .055 \text{ inch}$$
$$\theta_o = 67^o$$
$$R_s = .255\Omega$$

where it is desired to compute the cone loss down to a diameter of 0.10 inch, which would contain the diode chip. Eq. (5) then yields

$$\frac{P_L}{P_{in}} = .005$$

This result for the theoretical attenuation indicates that the ohmic losses in the quasi-optical mount exterior to the chip region are quite small at all the frequencies of interest.

3.0 EVALUATION OF A 1.5mm MIXER MOUNT

A biconical mount of the type described in Section 2 was constructed with a design wavelength of 1.5mm. A photograph of this mount is shown in Fig. 4. The radiating aperture of the mount is a circular hole 0.200 inches in diameter. As no local oscillator source was available at 200 Ghz the following mixer evaluation was performed at a frequency of 185 Ghz with the use of an available klystron with about 15mw output power.

3.1 Radiation Patterns of the Mixer Mount

In order to evaluate the radiation performance of the quasi-optical mixer mount, antenna patterns were measured at 185 Ghz. The mixer was mounted on an antenna pattern recorder turn table and illuminated with a 1 kHz square wave modulated klystron. The mixer diode was then used as a bolometer and the resulting antenna pattern recorded on a standard Scientific-Atlanta pattern recorder. It was assumed that the diode characteristics were essentially square law. The E and H plane antenna patterns of the quasi-optical mount are shown in Figs. 5 and 6. The patterns are quite well defined considering the measurement problems encountered at such high frequencies. The fine structure at the peaks of these patterns are believed due to range reflections.

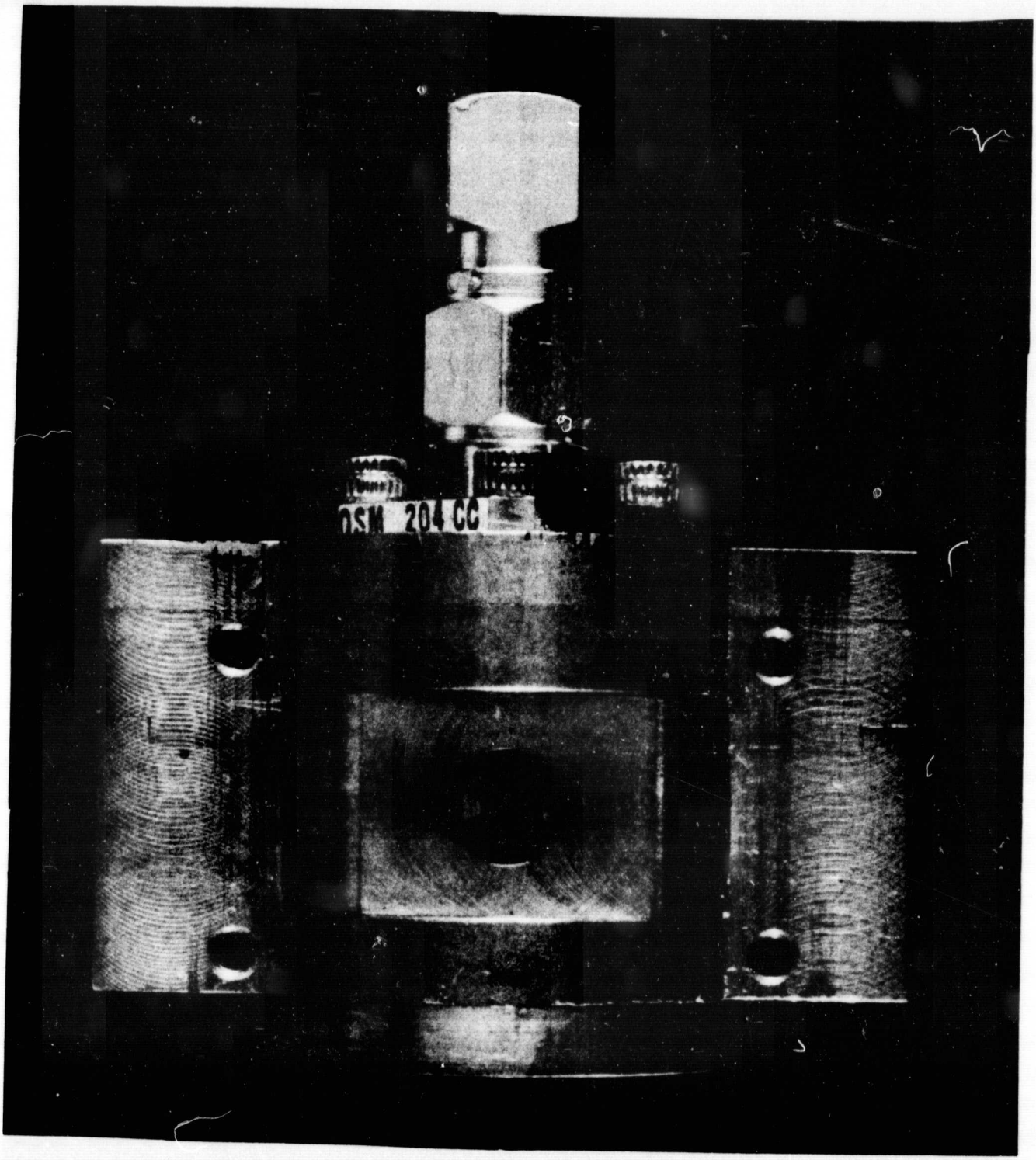

Figure 4. The 1.5 mm Quasi-optical Mixer Mount.

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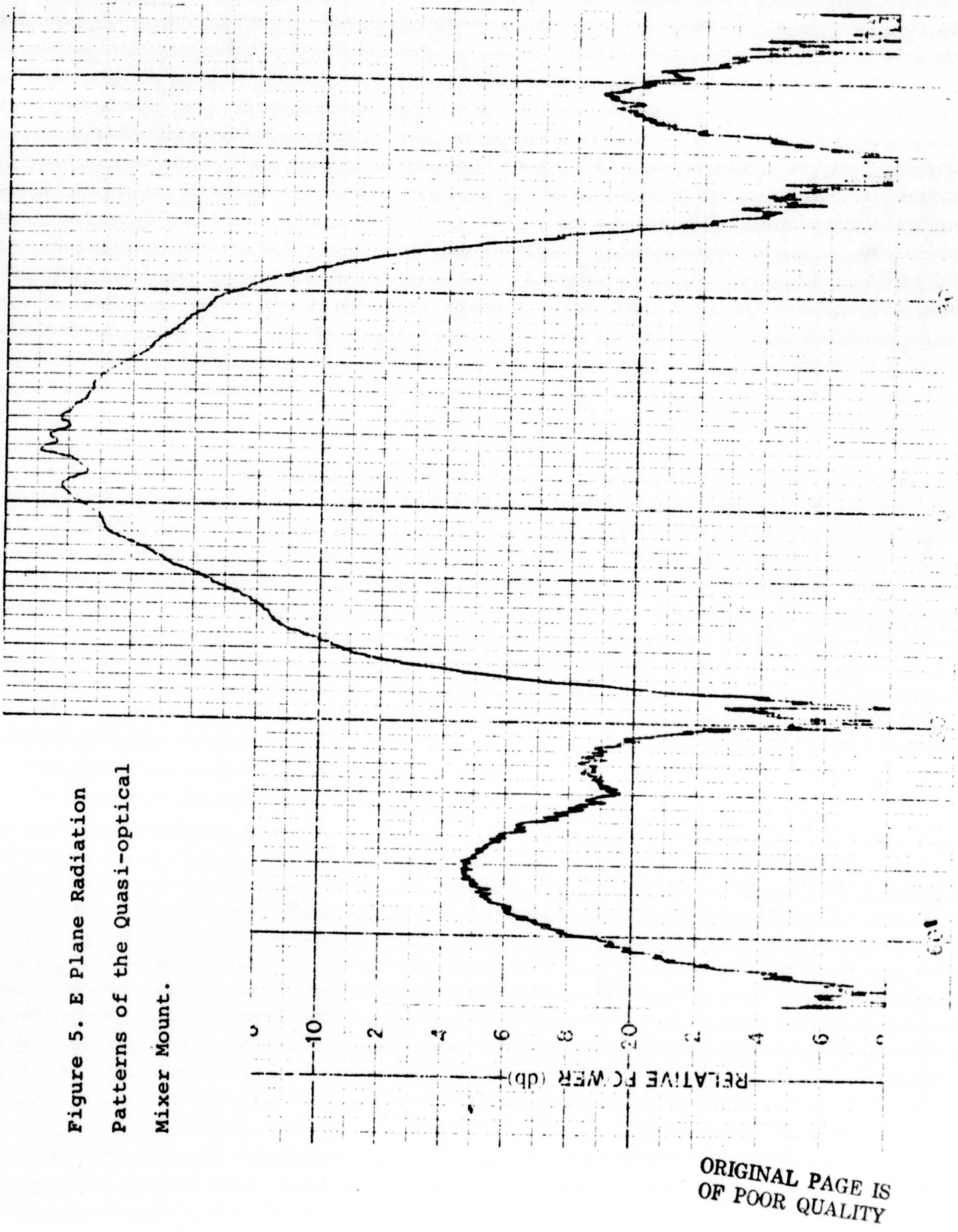

Figure 5. E Plane Radiation Patterns of the Quasi-optical Mixer Mount.

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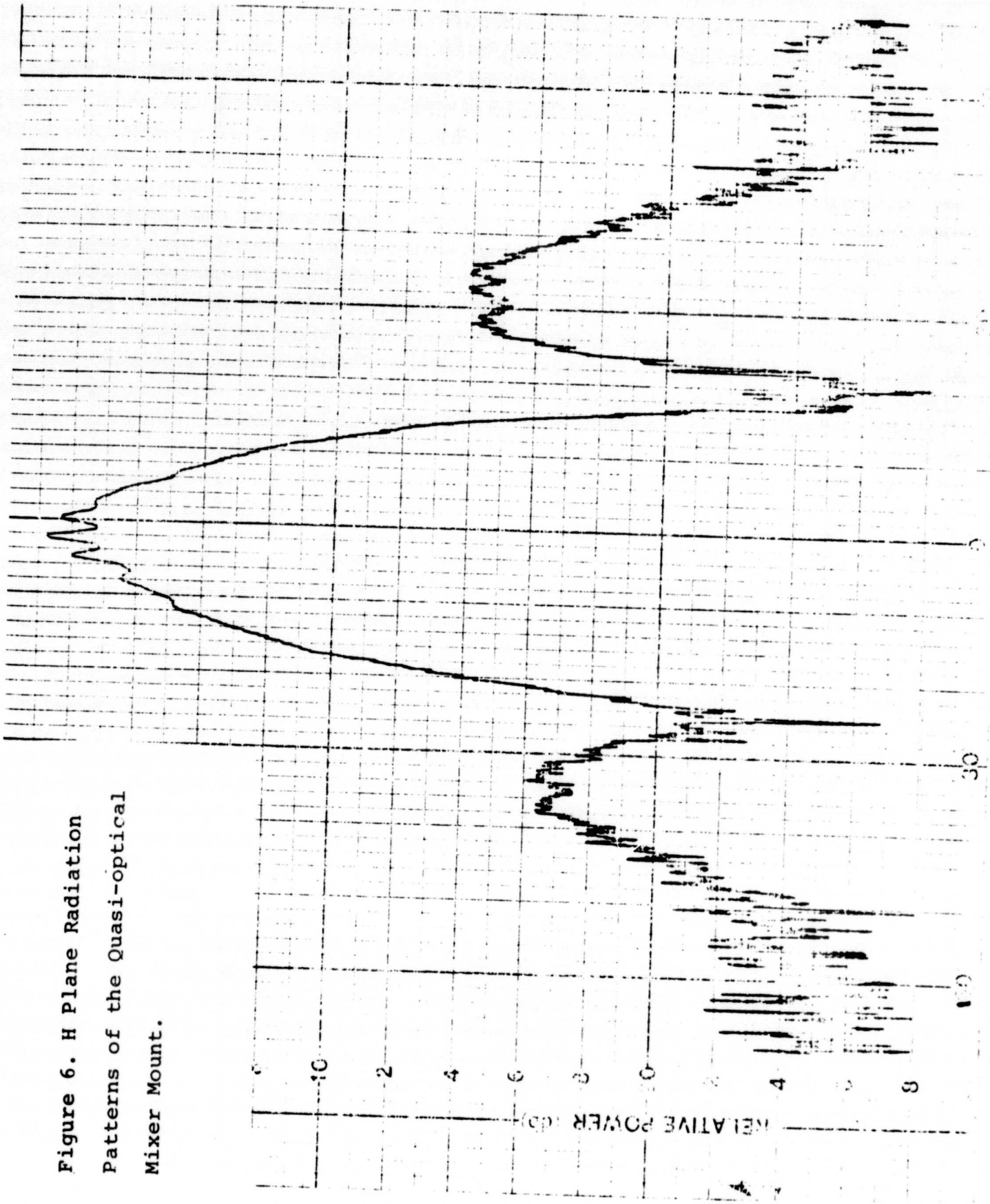

Figure 6. H Plane Radiation Patterns of the Quasi-optical Mixer Mount.

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It is seen that the H plane pattern has a 3 db width of about 16^{o} and an average sidelobe level of about -13 db. The E plane beamwidth is much wider being about 30^{o} at the 3 db points with an average sidelobe level of -17 db. These radiation characteristics are completely consistent with those of a circular aperture having a high illumination taper in elevation (E plane) and a uniform illumination in azimuth (H plane). The E plane taper results from the fact that the radiating aperture is being illuminated by a tapered beam which has diffracted somewhat from the bicone aperture. The uniform illumination in the H plane is caused by the fact that the aperture is intercepting the azimuthally uniform distribution of energy from the bicone in that plane.

3.2 I.F. Output Impedance

In order to determine the form of the matching network required to match the 1.5mm quasi-optical mixer mount to a 50Ω I.F. amplifier, the output impedance of the mixer was measured over the frequency range 0.8 - 2.0 Ghz. The measurement was made by biasing the mixer to a D-C voltage of 0.7V and then applying enough local oscillator energy at 185 Ghz to generate a D-C current of 0.7ma. It was noted that increasing the local oscillator drive to produce a current of 1.0ma did not change the measured impedance appreciably. The I.F. impedance was

then obtained by looking into the OSM connector of the mixer with a slotted line. The resulting impedance variation with frequency is shown on the Smith Chart of Fig. 7. The impedance values are referred to the 50 ohm OSM connector input.

Taking into account the electrical length of the fiber-glass bushing and OSM connector, the total path length from the chip to the end of the OSM connector is 1.38 inches. This length is measured along the center of the radiation path. The impedance of Figure 7 is closely predicted by replacing the chip with a lumped admittance of .22 + j .27 mhos and transforming this admittance back over the 1.38 inch path.

3.3 Measured Mixer Performance

In order to evaluate the mixer performance the mixer was mounted in an existing quasi-optical local oscillator injection system. The quasi-optical system focused energy down to the mixer with a one-inch diameter teflon lens which

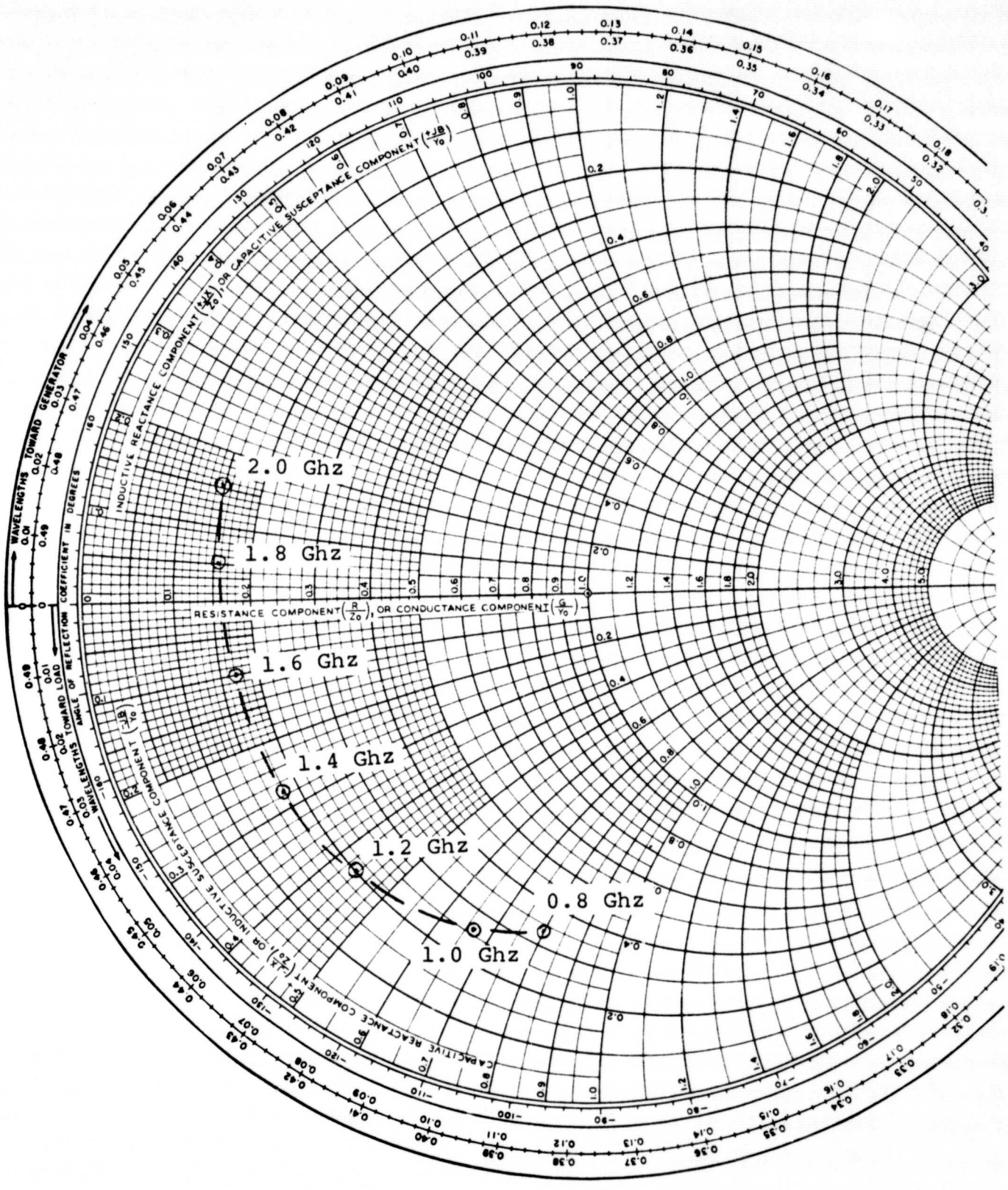

Figure 7. The Input Impedance to the 1.5 mm Mixer.

subtends 90° at its focal point. Due to the relatively narrow beamwidths of the quasi-optical mixer mount the lenses of the local oscillator injection system were not illuminated in an optimum fashion. Secondary radiation patterns of the one-inch lens-mixer combination were taken at 185 Ghz and the results are shown in Fig. 8 and 9. The H plane pattern has a half power beamwidth of 6° and the E plane pattern has a half power width of 4° consistent with the fact that the primary mixer illumination is more narrow in the H plane. Although the lenses of the local oscillator injection system were not illuminated properly a useful mixer evaluation could be performed since the lenses did provide good beam efficiencies allowing a direct measurement of conversion loss by intercepting all the beam energy with extended not and cold absorber loads. The improper lens illumination does give rise to the loss of local oscillator drive but the available klystron power at 185 Ghz was sufficient to overcome this effect.

The I.F. impedance of the mixer was matched to a 50Ω transistor amplifier that had a noise temperature of 185°K. The single sideband mixer conversion loss was measured to be -13 db by comparing liquid nitrogen load measurements at the input to the mixer and the input to the I.F. amplifier. A "Y" factor measurement of total system temperature yielded a single sideband temperature of about 10,000°K for the system.

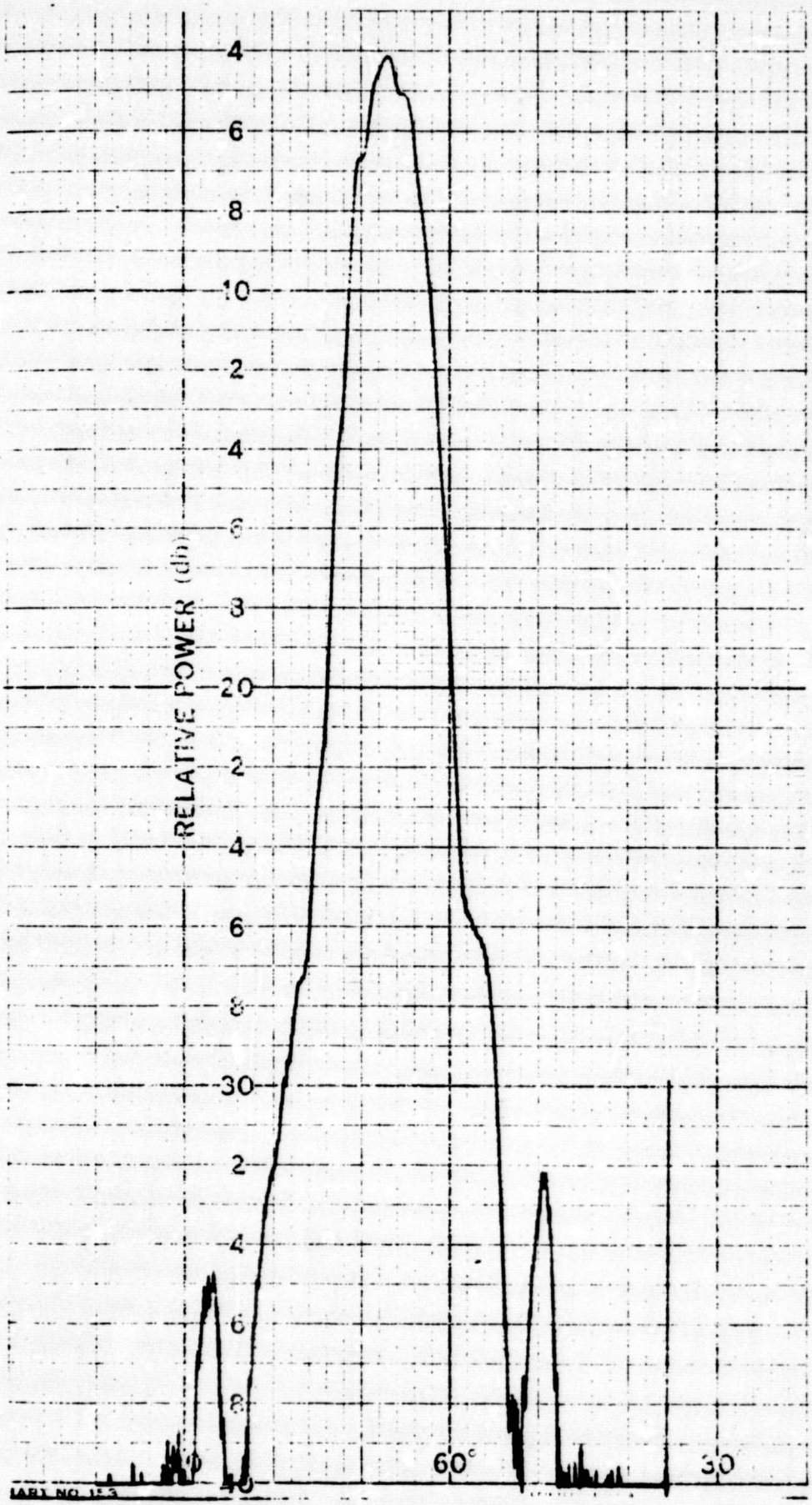

Figure 8. H Plane Antenna Pattern of the Lens-Mixer Combination.

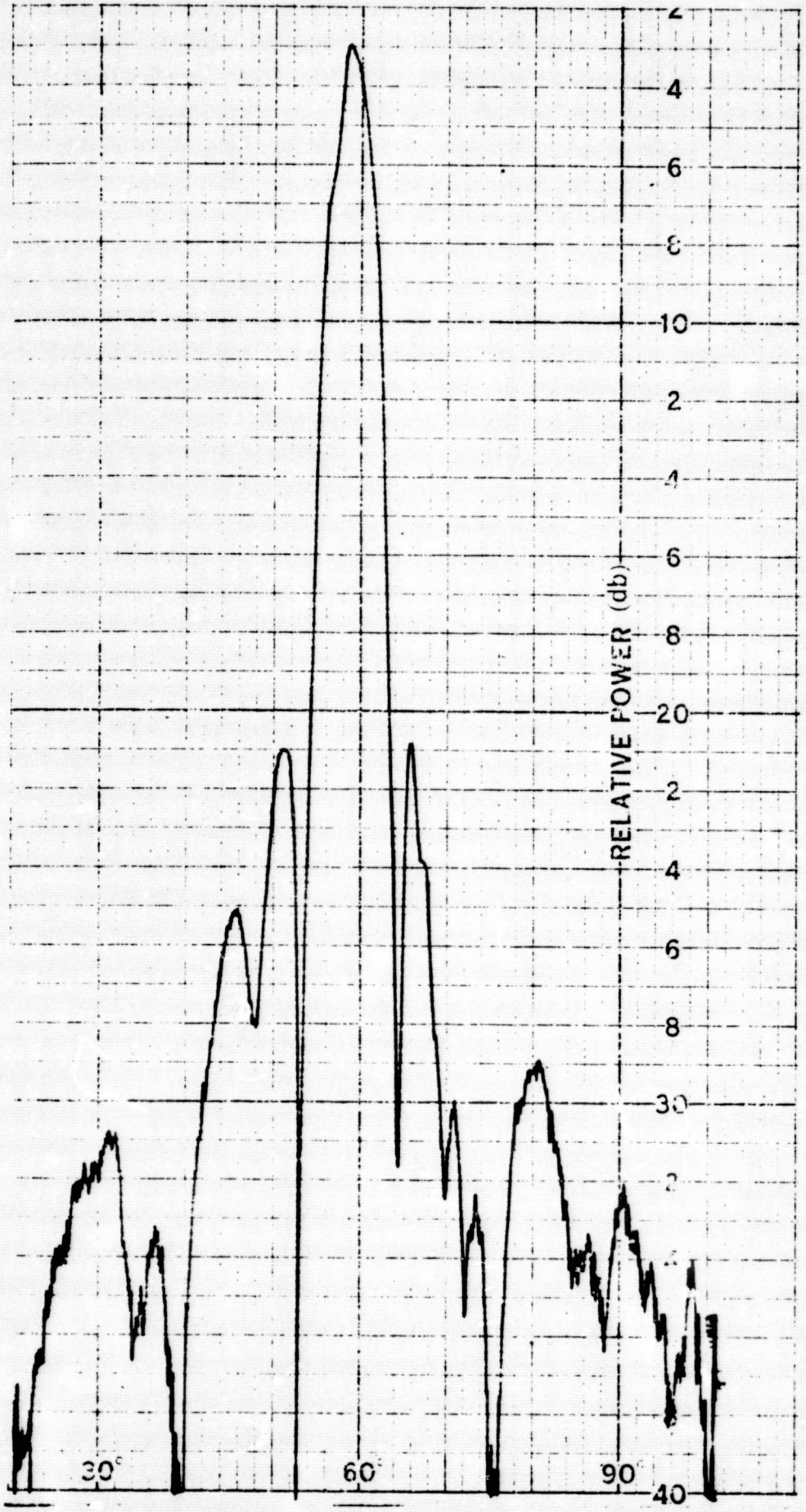

Figure 9. E Plane Antenna Pattern of the Lens-Mixer Combination.

4.0 A QUASI-OPTICAL FREQUENCY DOUBLER

A frequency doubler was constructed to investigate the use of quasi-optical circuitry for frequency multiplication. The output frequency of the doubler was chosen to be in the range from 110 to 120 Ghz so that a 70mw klystron which was available in the range from 55 to 60 Ghz could be used to drive the doubler. The general configuration of the doubler is shown in Fig. 10. The energy from the klystron is collimated into a 1.5 inch diameter beam by means of a horn-teflon lens combination. This energy is then focused down into a quasi-optical multiplier mount by means of a second lens and a reflection off of a dichroic plate. The dichroic plate is constructed so as to be highly reflective for the 55 to 60 Ghz klystron energy while at the same time being almost completely transmissive for the 110-120 Ghz energy which is generated as a second hormonic in the quasi-optical mount.

The 1.5 inch diameter beam output of the doubler was injected directly into the local oscillator input port of a 115 Ghz radiometer which is described in Ref. 1. A measure of the doubler performance was then obtained by observing the amount of D-C bias developed in the radiometer mixer by the local oscillator energy from the doubler.

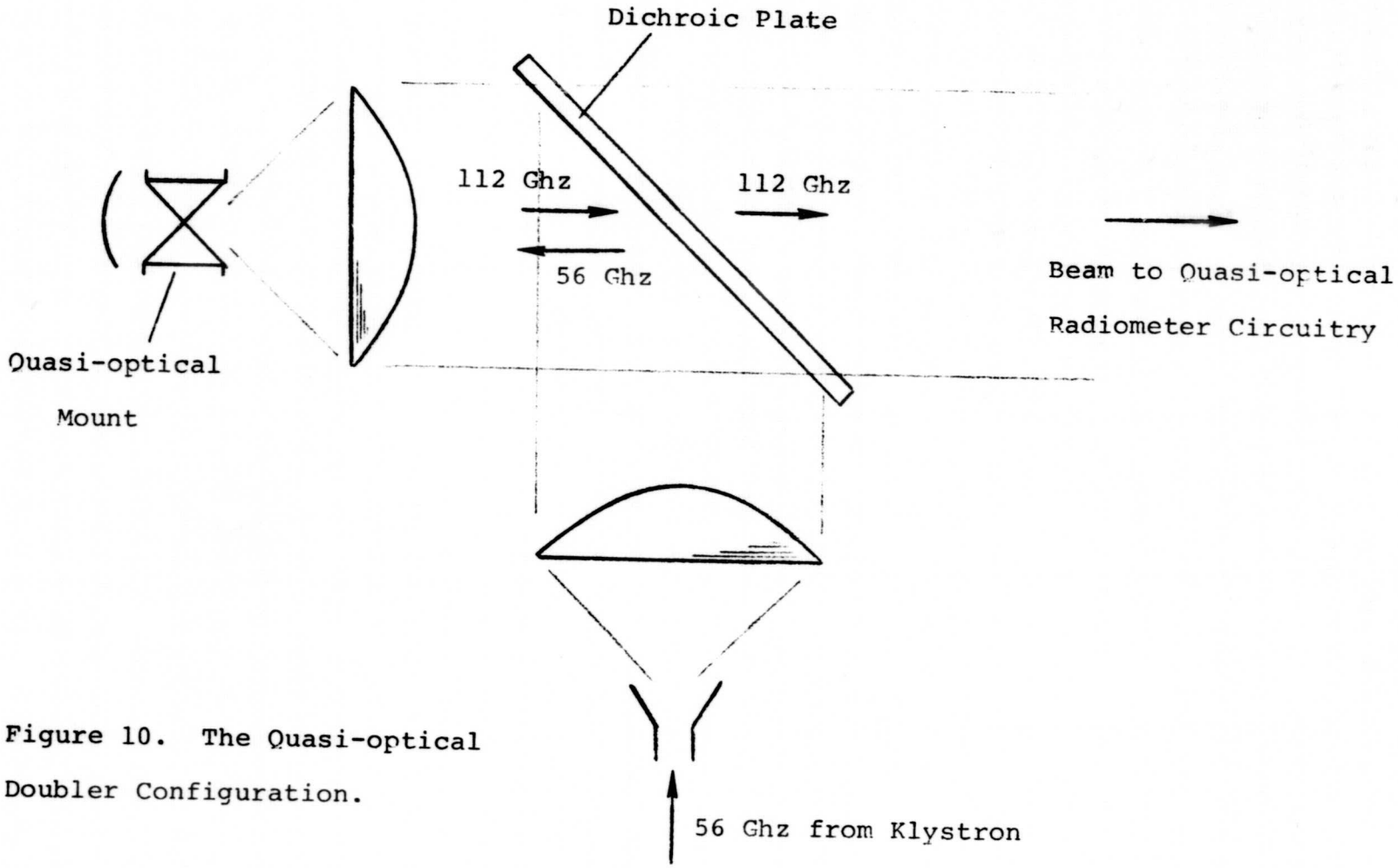

Figure 10. The Quasi-optical Doubler Configuration.

4.1 The Quasi-Optical Doubler Mount

The biconical mount for the Schottky diode doubler is shown in Fig. 11. The mount and diode chip are basically of the type described in Section 2. As can seen in the figure, the curved back-short has been modified so as to provide a large aperture for the 55 to 60 Ghz energy. The back-short is spherical with a radius of .229 inches. A 90^{o} sector of the back-short has been removed to provide the radiating aperture. The upper and lower bullets of the mount have a diameter of .484 inches. No attempts were made to optimize the mount in any way as this first attempt at frequency doubling was undertaken merely to demonstrate feasibility.

4.2 The Dichroic Plate

The dichroic plate was constructed by drilling a series of .044 inch diameter holes with center-to-center spacings of 0.050 inches over a 1.5 x 2.2 inch area of a .062 inch thick aluminum plate. The holes were then filled with paraffin wax so that each hole would act as a short length of circular dielectric loaded waveguide which could support the TE_{11} mode at 110 Ghz. By closely spacing the holes and dielectrically loadind them, grating effects were eliminated for the 45^{o} incidence angle on the plate. At 60 Ghz the waveguide holes are below cutoff and the plate is highly reflective.

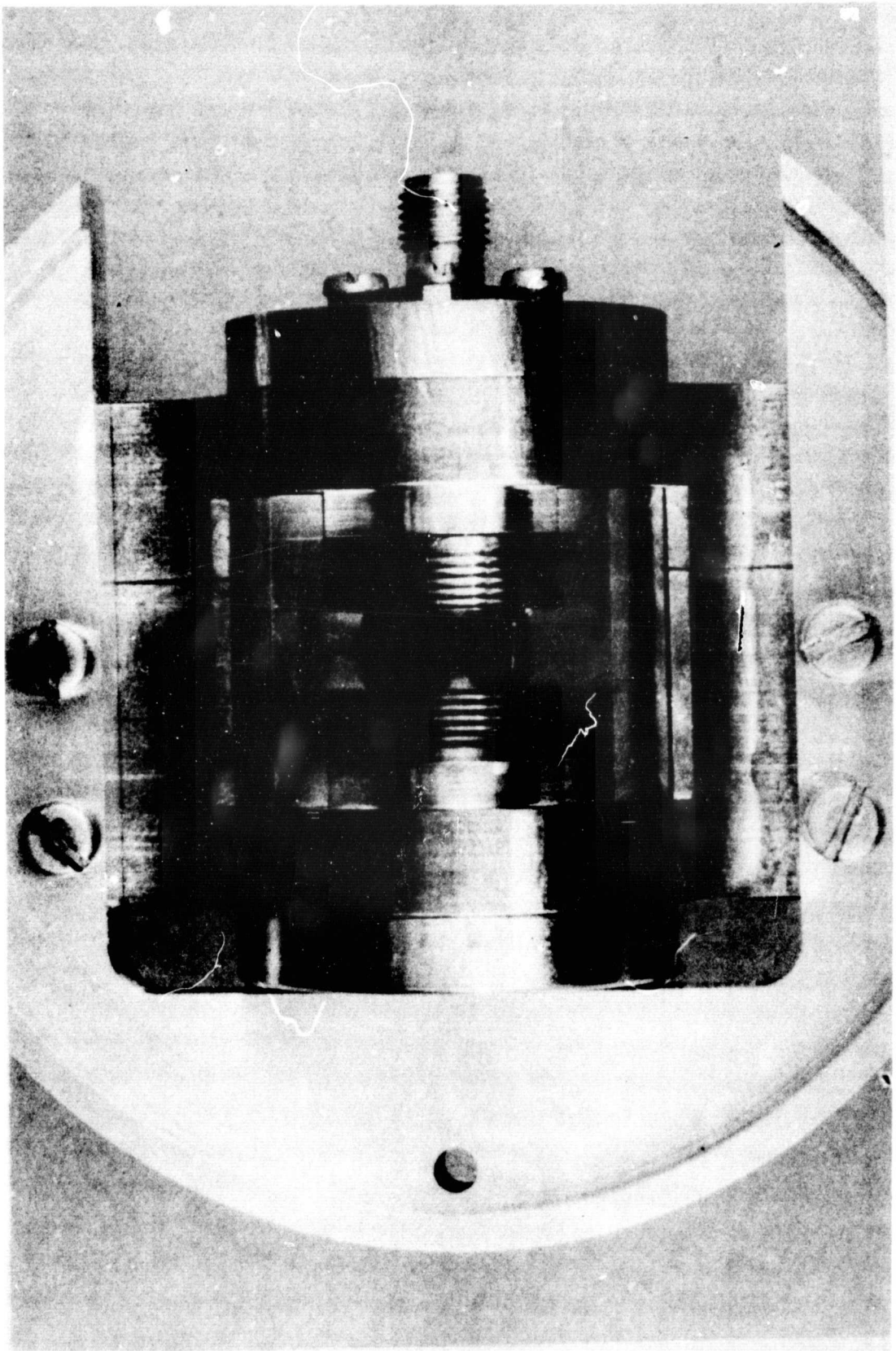

Figure 11. The Biconical Frequency Doubler Mount.

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4.3 Measured 56-112 Ghz Doubler Performance

Because of the fixed back-short construction of the quasi-optical doubler mount the doubler could not be tuned to an arbitrary frequency. Since it was only desired to demonstrate feasibility the klystron was tuned over its range to find a frequency at which the doubler performed. It was found that at 56 Ghz the doubler diode could be driven to burn out with the 70mw klystron input. It was determined that the whiskered diode contract would be destroyed at a point where the D-C self-bias of the diode was in the range of 14 to 18ma when no D-C bias voltage was applied to the diode. At 12ma of induced current an appreciable second harmonic output of the doubler was observed. Applying a positive or negative D-C bias voltage to the doubler diode was found to reduce the second harmonic output so the doubler diode OSM connector was shorted by a D-C milliameter. The doubler output at 112 Ghz developed 0.7ma of D-C current in the radiometer mixer which was biased to a voltage of 0.7 V. These levels of local oscillator power were sufficient to drive the radiometer to its usual performance levels. From a knowledge of the radiometer characteristics it is estimated that the output power of the doubler was about 5mw at 112 Ghz yielding a doubling efficiency of approximately 7%.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The quasi-optical mixer and doubler described in this report represents the first step in the development of non-waveguide Schottky diode devices which can be directly scaled to the higher frequencies. The noise performance of this first biconical mixer mount is roughly within 4db of the performance of the best waveguide mixers now measured at 185 Ghz with no serious attempts to optimize or enhance the quasi-optical mount performance. It is recommended that further development work be applied to the biconical mixer. The elements of the mixer mount which can give rise to losses such as the whisker, radiating aperture, back-short geometry, etc-should be studied in detail in order to provide improved conversion loss performance. In ivew of the meaningful measured performance of the mixer at 185 Ghz it is also recommended that the existing mount be immediately scaled to higher frequencies to obtain some idea of the frequency roll-off of the diode chip and the problems to be encountered in implementing the design at higher frequencies.

The quasi-optical doubler demonstrated the feasibility and ease with which quasi-optical circuitry can be used to inject and extract energy to and from the diode multiplier element. The marginally useful measured power input levels at 112 Ghz indicate that efficient frequency doubling with a single diode element may be difficult. It is recommended that

a new doubler design be implemented using two diodes in a balanced tandem configuration in order to enhance the power handling capabilities and the second harmonic output generation.

6.0 NEW TECHNOLOGY

The quasi-optical biconical mount described in Section 2 of this report is a reportable item of new technology. The use and configuration of the quasi-optical biconical circuitry for this application is novel and innovative and believed to be an original invention reduced to practice in this application for the first time.

7.0 REFERENCES

1. Gustincic, J.J., "Millimeter Airborne Radiometer Front End," Interim Report No. TR077, JPL Contract No. 954294, 7 April 1976, pp. 7-13.